TOWARDS DIFFERENTIAL TOP PAIR PRODUCTION AT NNLO

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Based on work done in collaboration with:
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Top Pair Production At The LHC

- Interesting signal. Rich phenomenology. Important in new physics searches…

- Top quark pairs are copiously produced at the LHC

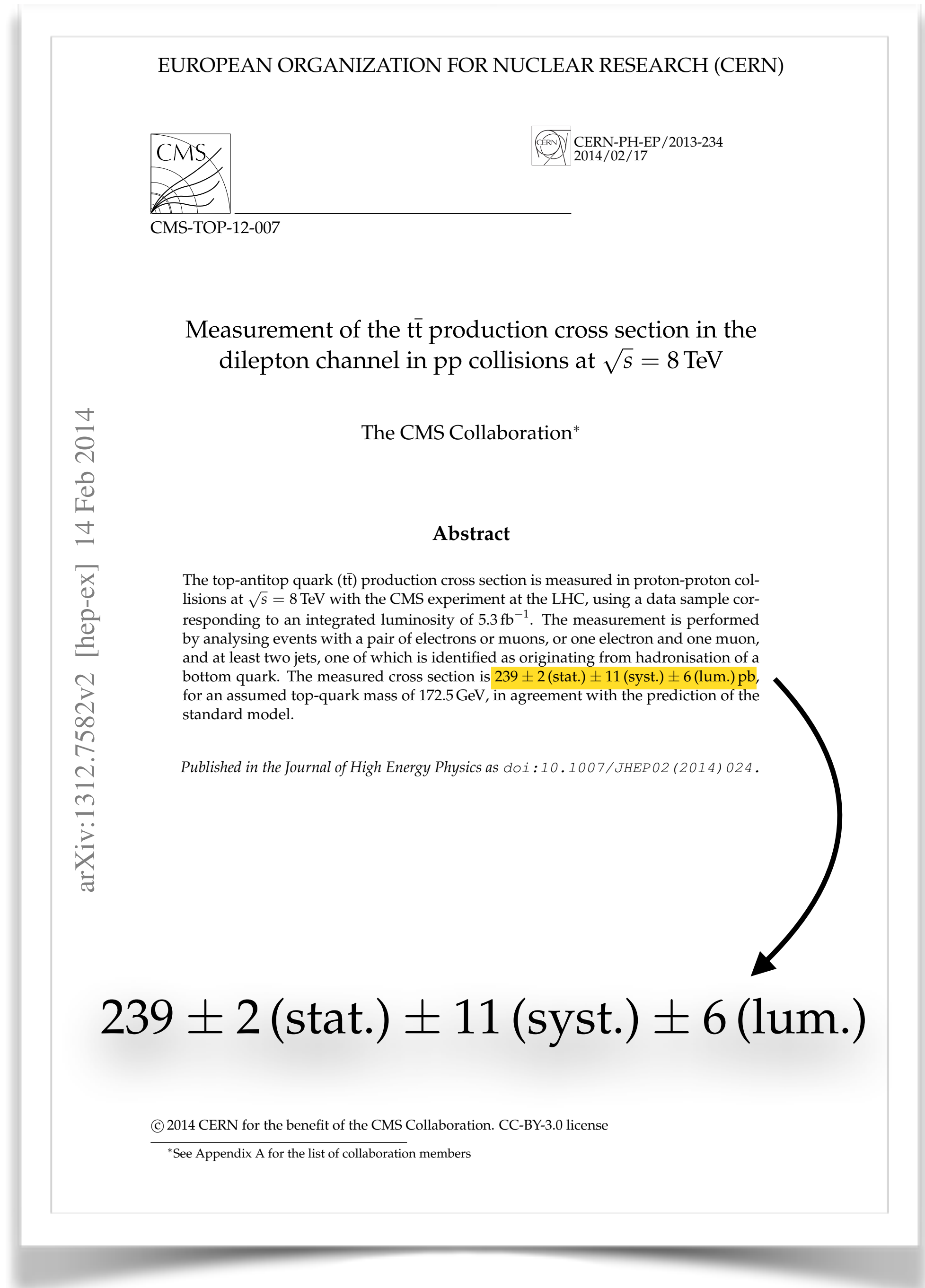
$$\sigma_{t\bar{t}+X}(\sqrt{s}=7\,\mathrm{TeV}) \sim 170\,\mathrm{pb}$$

$$\sigma_{t\bar{t}+X}(\sqrt{s}=8\,\mathrm{TeV}) \sim 250\,\mathrm{pb}$$

$$\sigma_{t\bar{t}+X}(\sqrt{s}=14\,\mathrm{TeV}) \sim 950\,\mathrm{pb}$$

- Abundant statistics. Expected experimental error ~5%

- Need theoretical predictions with similar accuracy
  - Requires computations through higher orders in perturbation theory



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2014/02/17

arXiv:1312.7582v2 [hep-ex] 14 Feb 2014

Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The top-antitop quark ($t\bar{t}$) production cross section is measured in proton-proton collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ with the CMS experiment at the LHC, using a data sample corresponding to an integrated luminosity of $5.3\,\mathrm{fb}^{-1}$. The measurement is performed by analysing events with a pair of electrons or muons, or one electron and one muon, and at least two jets, one of which is identified as originating from hadronisation of a bottom quark. The measured cross section is $239 \pm 2\,(\mathrm{stat.}) \pm 11\,(\mathrm{syst.}) \pm 6\,(\mathrm{lum.})\,\mathrm{pb}$, for an assumed top-quark mass of $172.5\,\mathrm{GeV}$, in agreement with the prediction of the standard model.

Published in the Journal of High Energy Physics as doi:10.1007/JHEP02(2014)024.

$$239 \pm 2\,(\mathrm{stat.}) \pm 11\,(\mathrm{syst.}) \pm 6\,(\mathrm{lum.})$$

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*See Appendix A for the list of collaboration members

Top Pair Production At The LHC: State Of The Art

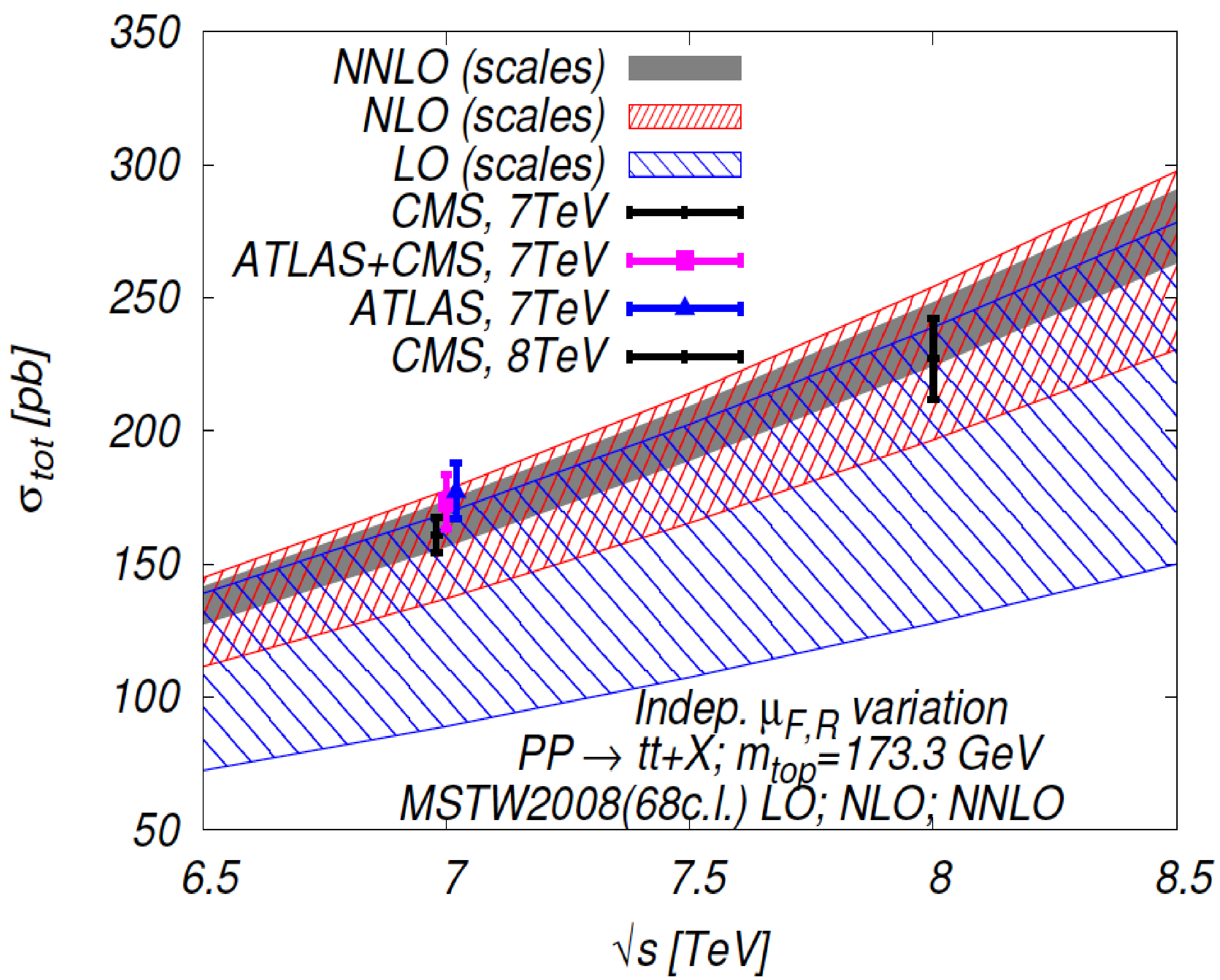
- NLO QCD corrections: Ellis, Dawson, Nason; Beenakker, Kuijf, van Neerven, Smith '89
- NLO EW corrections: Beenakker, Bernreuther, Denner, Fuecker, Hollik, Kao, Kollar, Kühn, Ladinsky, Mertig, Moretti, Nolten, Ross, Sack, Scharf, Si, Uwer, Wackenroth, Yuan
- Threshold resummation and Coulomb corrections: Ahrens, Banfi, Berger, Bonciani, Catani, Contopanagos, Czakon, Ferroglia, Frixione, Kidonakis, Kiyo, Kühn, Laenen, Mangano, Mitov, Moch, Nason, Neubert, Pecjak Ridolfi, Steinhauser, Sterman, Uwer, Vogt, Yang

Yield a theoretical uncertainty of ~10%

To match theory and experimental accuracies at the LHC, cross sections for top pair production must be calculated through NNLO in pQCD

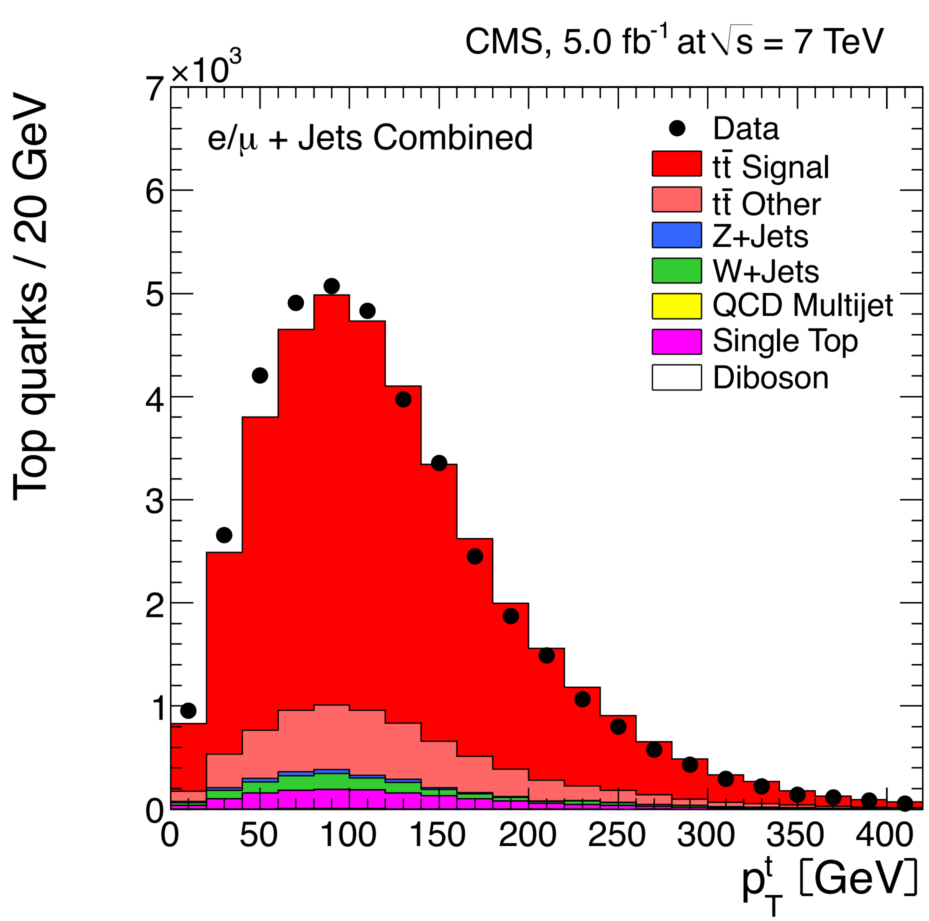
Top Pair Production At The LHC: State Of The Art

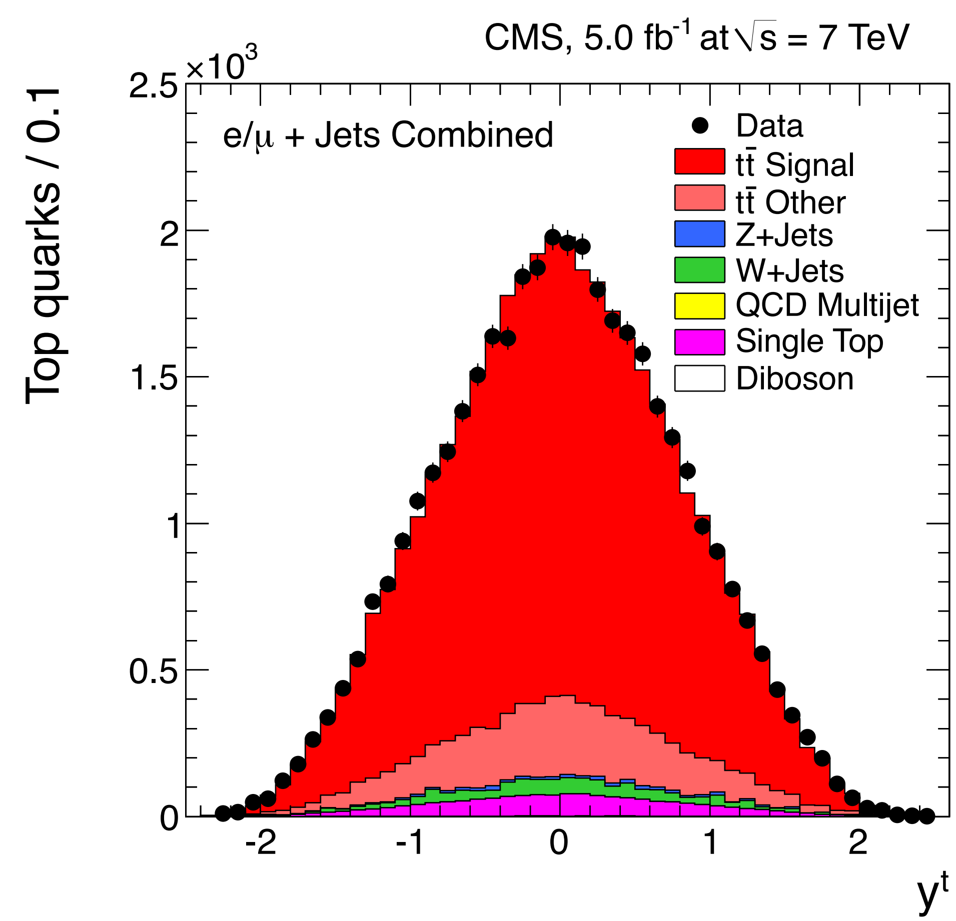
- Calculation of the total NNLO cross section completed [Czakon, Fiedler, Mitov '13]
  - Combined with NNLL resummation
  - Theoretical and experimental uncertainties of similar sizes (percent level)



Differential Top Pair Production

- Differential distributions probe the dynamics of top quark production
  - Important in order to search for new physics as deviations from SM predictions





Need NNLO predictions for $\frac{\mathrm{d}\sigma}{\mathrm{d}X}$ with $X = p_T^t,\ p_T^{t\bar{t}},\ y^t,\ y^{t\bar{t}},\ m_{t\bar{t}}$

- Approximate results available, including decays (A. Broggio's talk)

Differential Top Pair Production

- Goal: fully differential event generator for $t\bar{t}$ production at NNLO

- This talk:
  - Status of our NNLO calculation for the $q\bar{q}$ channel (leading-color + N_l only)

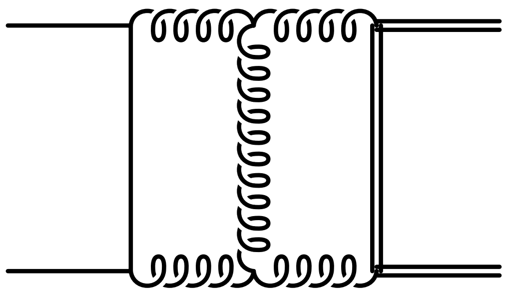
$$\mathrm{d}\hat{\sigma}_{q\bar{q},NNLO} = N_c C_F \left[N_c^2 A + B + \frac{C}{N_c^2} + N_l \left(N_c D_l + \frac{E_l}{N_c} \right) + N_h \left(N_c D_h + \frac{E_h}{N_c} \right) \right. \\ \left. + N_l^2 F_l + N_l N_h F_{lh} + N_h^2 F_h \right]$$

  - Preliminary differential distributions as a proof of principle

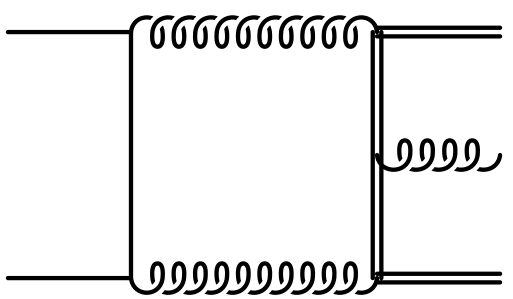
Ingredients For Top Pair Production At NNLO

- LO and NLO fully differential cross sections
  - Known [Ellis, Dawson, Nason '89; Beenakker, Kuijf, van Neerven, Smith '89]
  - Re-derived using NLO antenna subtraction [GA, Gehrmann-De Ridder '11]

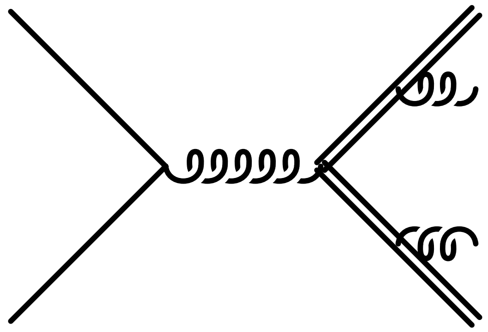
- Two-loop 2→2 matrix elements
  - Use analytic results (A. von Manteuffel's talk) [Bonciani, Ferroglia, Gehrmann, Maître, v. Manteuffel, Studerus]



- One-loop 2→3 matrix elements
  - Obtained numerically with OpenLoops [Cascioli, Meierhöfer, Pozzorini]
    - ✓ Color structure handled algebraically
    - ✓ Quadruple precision evaluation in soft limit



- Tree-level 2→4 matrix elements



Ingredients For Top Pair Production At NNLO

$$\mathrm{d}\hat{\sigma}_{NNLO} = \int_{\mathrm{d}\Phi_4} \mathrm{d}\hat{\sigma}^{RR}_{NNLO} + \int_{\mathrm{d}\Phi_3} \left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO} + \mathrm{d}\hat{\sigma}^{MF,1}_{NNLO} \right) + \int_{\mathrm{d}\Phi_2} \left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO} + \mathrm{d}\hat{\sigma}^{MF,2}_{NNLO} \right)$$

- $\mathrm{d}\hat{\sigma}^{RV}_{NNLO}\,,\ \mathrm{d}\hat{\sigma}^{VV}_{NNLO} \longrightarrow$ explicit IR poles from loop integration
- $\int_{\mathrm{d}\Phi_4} \mathrm{d}\hat{\sigma}^{RR}_{NNLO}\,,\ \int_{\mathrm{d}\Phi_3} \mathrm{d}\hat{\sigma}^{RV}_{NNLO} \longrightarrow$ implicit IR poles from PS integration over single and double unresolved regions

Need a procedure to isolate and cancel all IR singularities, and assemble all parts in a parton-level event generator

Antenna Subtraction At NNLO

$$
\begin{aligned}
\mathrm{d}\hat{\sigma}_{NNLO} = &\int_{\mathrm{d}\Phi_4} \left(\mathrm{d}\hat{\sigma}^{RR}_{NNLO} - \mathrm{d}\hat{\sigma}^{S}_{NNLO} \right) \\
&+ \int_{\mathrm{d}\Phi_3} \left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{VS}_{NNLO} + \mathrm{d}\hat{\sigma}^{MF,1}_{NNLO} + \int_1 \mathrm{d}\hat{\sigma}^{S,1}_{NNLO} \right) \\
&+ \int_{\mathrm{d}\Phi_2} \left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO} + \mathrm{d}\hat{\sigma}^{MF,2}_{NNLO} + \int_1 \mathrm{d}\hat{\sigma}^{VS}_{NNLO} + \int_2 \mathrm{d}\hat{\sigma}^{S,2}_{NNLO} \right)
\end{aligned}
$$

- Introduce double real and real-virtual subtraction terms $\mathrm{d}\hat{\sigma}^{S}_{NNLO}$, $\mathrm{d}\hat{\sigma}^{VS}_{NNLO}$ and add them back in integrated form

- The integrated double real subtraction term is split as

$$
\int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\hat{\sigma}^{S}_{NNLO} = \int_{\mathrm{d}\Phi_{m+1}} \int_1 \mathrm{d}\hat{\sigma}^{S,1}_{NNLO} + \int_{\mathrm{d}\Phi_{m}} \int_2 \mathrm{d}\hat{\sigma}^{S,2}_{NNLO}
$$

- Each PS integrand is free of explicit poles, well behaved in singular regions, and can be integrated numerically in D=4

Double Real Subtraction Terms

Use a color decomposition of the double real (2 ➞ (m+2)) amplitude

$$d\hat{\sigma}^{RR}_{NNLO} = \mathcal{N}^{RR}_{NNLO} \sum_{\text{perms}} d\Phi_{m+2}(p_3, \ldots, p_{m+4}; p_1, p_2) |\mathcal{M}^0_{m+4}(\hat{1}, \hat{2}, 3, \ldots)|^2 J^{(m+2)}_m(p_3, \ldots, p_{m+4})$$

- $|\mathcal{M}^0_{m+4}|^2$singular in single and double unresolved limits (soft, collinear, …)
  - Factorization in IR singular limits well known. Described by universal unresolved factors [Campbell, Glover '98; Catani Grazzini '99]. E.g. single and double soft limits:

$$|\mathcal{M}^0_{m+4}(\ldots, p_i, p_j, p_k, \ldots)|^2 \xrightarrow{p_j \to 0} \mathcal{S}(i, j, k) |\mathcal{M}^0_{m+3}(\ldots, p_i, p_k, \ldots)|^2$$

$$|\mathcal{M}^0_{m+4}(\ldots, p_i, p_j, p_k, p_l, \ldots)|^2 \xrightarrow{p_j, p_k \to 0} \mathcal{S}(i, j, k, l) |\mathcal{M}^0_{m+2}(\ldots, p_i, p_l, \ldots)|^2$$

- Unresolved factors captured by three and four-parton tree-level antenna functions

$$X^0_3(i, j, k) = S_{ijk,IK} \frac{|\mathcal{M}^0_3(i, j, k)|^2}{|\mathcal{M}^0_2(I, K)|^2}$$

One unresolved parton (j)

$$X^0_4(i, j, k, l) = S_{ijkl,IL} \frac{|\mathcal{M}^0_4(i, j, k, l)|^2}{|\mathcal{M}^0_2(I, L)|^2}$$

Two unresolved partons (j,k)

Double Real Subtraction Terms

- $\mathrm{d}\hat{\sigma}^{S}_{NNLO}$ contains three different antenna structures
  - $X_3^0(i,j,k)|\mathcal{M}_{m+3}(\ldots,p_I,p_K,\ldots)|^2$ $\longrightarrow$ Single unresolved limits
  - $X_4^0(i,j,k,l)|\mathcal{M}_{m+2}(\ldots,p_I,p_L,\ldots)|^2$ $\longrightarrow$ Color-connected double unresolved limits
  - $X_3^0\,X_3'^{\,0}|\mathcal{M}^0_{m+2}|^2$ $\longrightarrow$ (Almost) Color-unnconnected double unresolved limits

- 3→2 and 4→2 on-shell momentum mappings

$$\{p_i,p_j,p_k\}\to\{p_I,p_K\} \qquad \{p_i,p_j,p_k,p_l\}\to\{p_I,p_L\}$$

  - Conserve momentum in reduce matrix elements
  - Collapse to appropriate kinematics in each unresolved limit

Real-Virtual Subtraction Terms

Use a color decomposition of the tree and loop (2 → (m+1)) amplitudes

$$\mathrm{d}\hat{\sigma}^{RV}_{NNLO} = \mathcal{N}^{RV}_{NNLO} \sum_{\text{perms}} \mathrm{d}\Phi_{m+1}(p_3,\ldots,p_{m+3};p_1,p_2)|\mathcal{M}^1_{m+3}(\hat{1},\hat{2},3,\ldots)|^2 J^{(m+1)}_m(p_3,\ldots,p_{m+3})$$

- $|\mathcal{M}^1_{m+3}|^2$ singular in single unresolved limits. Well known factorization [Bern, Catani, Dixon, Dunbar, Kosower, Uwer, …]

$$|\mathcal{M}^1_{m+3}|^2 \xrightarrow{j \text{ unresolved}} \mathrm{Sing}^0 \times |\mathcal{M}^1_{m+2}|^2 + \mathrm{Sing}^1 \times |\mathcal{M}^0_{m+2}|^2$$

- Accordingly, $\mathrm{d}\hat{\sigma}^{VS}_{NNLO}$ is constructed as

$$\begin{aligned}|\mathcal{M}^1_{m+3}(\ldots,p_i,p_j,p_k,\ldots)|^2 \to X^0_3(i,j,k)|\mathcal{M}^1_{m+2}(\ldots,p_I,p_K,\ldots)|^2 \\ +X^1_3(i,j,k)|\mathcal{M}^0_{m+2}(\ldots,p_I,p_K,\ldots)|^2\end{aligned}$$

- One-loop antennae

$$X^1_3(i,j,k) = S_{ijk,IK}\,\frac{|\mathcal{M}^1_3(i,j,k)|^2}{|\mathcal{M}^0_2(I,K)|^2} - X^0_3(i,j,k)\,\frac{|\mathcal{M}^1_2(I,K)|^2}{|\mathcal{M}^0_2(I,K)|^2}$$

Integrated Subtraction Terms

Subtraction terms must be integrated and added back in lower multiplicity final states

- Phase space factorization (different in f-f, i-f, and i-i cases). E.g.

$$\mathrm{d}\Phi_{m+2}(\ldots,p_i,p_j,p_k,p_l,\ldots) = \mathrm{d}\Phi_m(\ldots,p_I,p_L,\ldots) \times \mathrm{d}\Phi_{X_{ijkl}}(p_i,p_j,p_k,p_l)$$

- Integrated antennae are the inclusive integrals

$$\mathcal{X}^0_{ijkl}(\epsilon, s_{IL}) = \frac{1}{C(\epsilon)^2} \int \mathrm{d}\Phi_{X_{ijkl}}(p_i,p_j,p_k,p_l) X^0_4(i,j,k,l)$$

- Integrated subtraction terms given by

$$\int_2 \mathrm{d}\hat{\sigma}^{S,2}_{NNLO} \sim C(\epsilon)^2 \mathrm{d}\Phi_m(\ldots,p_I,p_L,\ldots)\mathcal{X}^0_{ijkl}(\epsilon, s_{IL})|\mathcal{M}_{m+2}(\ldots,p_I,p_L,\ldots)|^2 J^{(m)}_m(\ldots,p_I,p_L,\ldots)$$

- $\int_1 \mathrm{d}\hat{\sigma}^{S,1}_{NNLO}$ and $\int_1 \mathrm{d}\hat{\sigma}^{VS}_{NNLO}$ obtained analogously

NNLO Antenna Subtraction With Massive Quarks

Slide from J. Currie's talk

NNLO dijets at the LHC
└Antenna Subtraction

Antenna Subtraction Toolbox

Many tools needed for implementation:

- final-final phase space mappings [Kosower '03]
- FF X_3^0, X_4^0, X_3^1 antennae [Gehrmann-De Ridder, Gehrmann, Glover, '04, '05]
- integrated FF antennae [Gehrmann-De Ridder, Gehrmann, Glover, '05]

$\Rightarrow$ $e^+e^- \to$ 3 jets at NNLO [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich, '07, Weinzierl '08]

Since then, extended for hadronic initial-states:

- initial-final + initial-initial mappings [Daleo, Gehrmann, Maître, '07]
- integrated IF X_3^1, X_4^0 [Daleo, Gehrmann-De Ridder, Gehrmann, Luisoni, '10]
- integrated II X_4^0 [Boughezal, Gehrmann-De Ridder, Ritzmann, '11. Gehrmann, Ritzmann '12]
- integrated II X_3^1 [Gehrmann, Monni, '11]

All tools exist for hadron-hadron scattering

[Glover, Pires, '10. Gehrmann De-Ridder, Glover, Pires, '12. Gehrmann De-Ridder, Gehrmann, Glover, Pires ,'13. JC, Glover, Wells, '13. JC, Gehrmann De-Ridder, Glover, Pires, '14.]

True for observables with massless partons

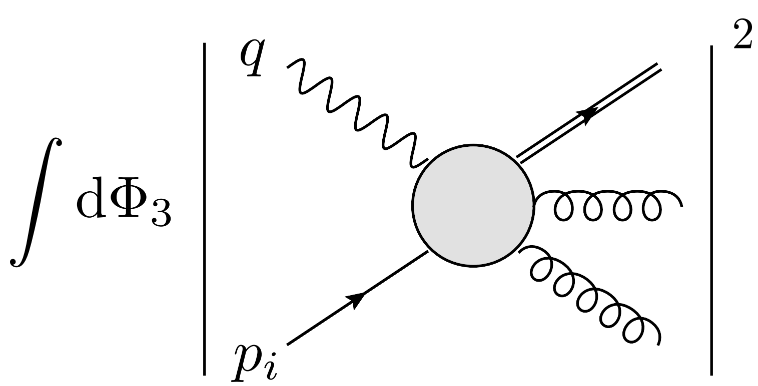
Challenge: extend NNLO antenna subtraction method to treat massive quarks.

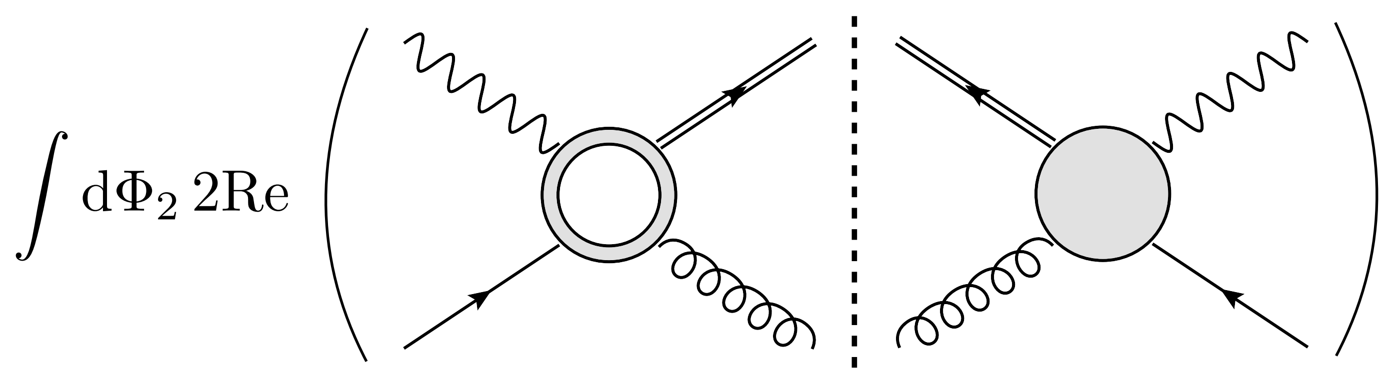
- Re-derive phase space mappings and factorizations
- Compute and integrate NLO and NNLO massive antennae

Integrated Massive Antennae

- Massless antennae: all known [Boughezal, Daleo, Gehrmann, Gehrmann-De Ridder, Glover, Luisoni, Maître, Ritzmann]

- Massive antennae: incomplete
  - Three parton tree-level: all known [Gehrmann-De Ridder, Ritzmann '09; GA, Gehrmann-De Ridder '11]
  - Four parton tree-level
    - Final-final: $\mathcal{A}^0_{Qgg\bar{Q}}$, $\mathcal{B}^0_{Qq\bar{q}\bar{Q}}$ [Bernreuther, Bogner, Dekkers]
    - Initial-final: $\mathcal{B}^0_{q,Qq'\bar{q}'}$, $\mathcal{E}^0_{g,Qq\bar{q}}$, $\widetilde{\mathcal{E}}^0_{g,Qq\bar{q}}$ [GA, Dekkers, Gehrmann-De Ridder '12]
    - More integrated antennae needed for $q\bar{q} \to t\bar{t} + X$ at NNLO: $\mathcal{A}^0_{q,Qgg}$, $\mathcal{A}^1_{q,Qg}$





- Multiple scales: m^2_{top}, q^2, $p_i \cdot q$
- Coupled differential equations for master integrals

Subtraction Terms For Top Pair Production In The Quark-Antiquark Channel

Where we now stand:

	Leading color	N_l
$\int_{\mathrm{d}\Phi_4}\left(\mathrm{d}\hat{\sigma}^{R}_{NNLO}-\mathrm{d}\hat{\sigma}^{S}_{NNLO}\right)$	✓[1]	✓[2]
$\int_{\mathrm{d}\Phi_3}\left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO}-\mathrm{d}\hat{\sigma}^{T}_{NNLO}\right)$	✓[1]	✓[3]
$\int_{\mathrm{d}\Phi_2}\left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO}-\mathrm{d}\hat{\sigma}^{U}_{NNLO}\right)$	✗*	✓[3]

1 [GA, Gehrmann-De Ridder, Meierhöfer, Pozzorini '14]
2 [GA, Gehrmann-De Ridder '11]
3 [GA, Gehrmann-De Ridder (in preparation)]

* Integrated massive antennae $\mathcal{A}^0_{q,Qgg}$ and $\mathcal{A}^1_{q,Qg}$ still missing. In progress.

Double Real Contributions

- Subtraction terms for partonic processes
  - $q\bar{q} \to t\bar{t}q'\bar{q}'$ [GA, Gehrmann-De Ridder '11]
  - $q\bar{q} \to t\bar{t}gg$ (leading-color only) [GA, Gehrmann-De Ridder, Meierhöfer, Pozzorini '14]

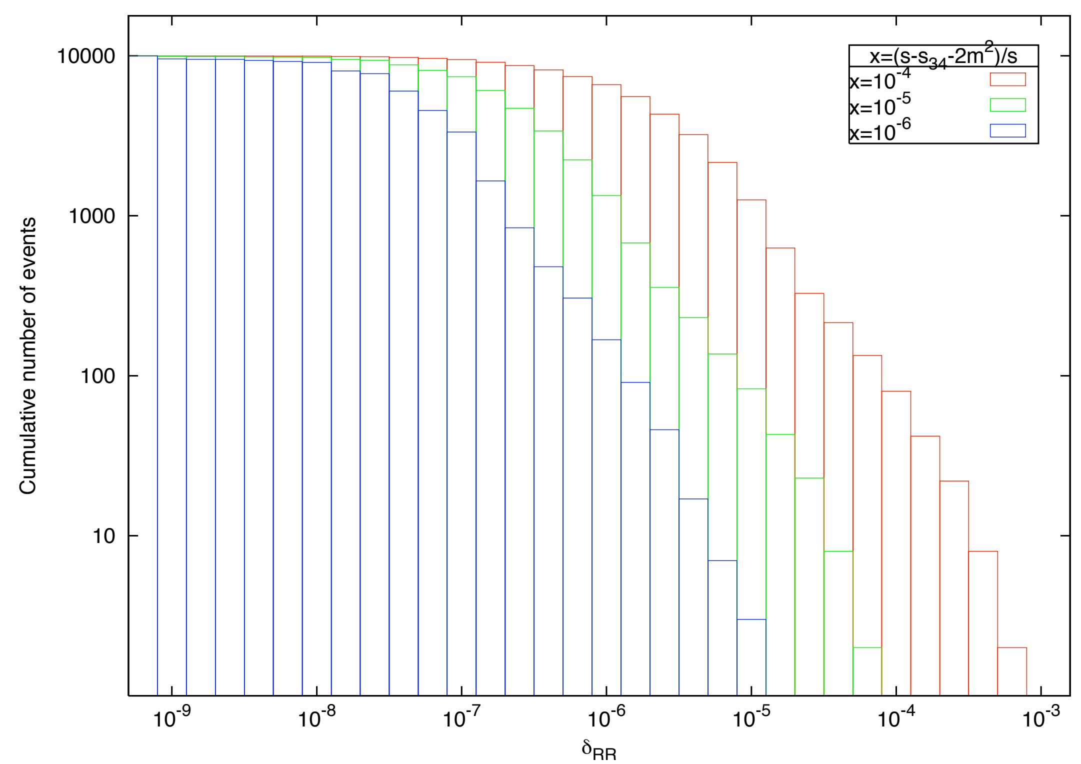
- Check of convergence
  - Generate events near every singular region
  - Control proximity to singularities with a control variable x (specific to each limit)
  - For each event, compute

$$\delta_{RR} = \left| \frac{\mathrm{d}\hat{\sigma}^{RR}_{NNLO}}{\mathrm{d}\hat{\sigma}^{S}_{NNLO}} - 1 \right|$$

  - Convergence of $\mathrm{d}\hat{\sigma}^{S}_{NNLO}$ to $\mathrm{d}\hat{\sigma}^{RR}_{NNLO}$ observed in cumulative histograms in δ_{RR}

- Similar (good) convergence observed in all single and double unresolved limits

Double soft limit of $q\bar{q} \to t\bar{t}gg$



Real Virtual Contributions

- Partonic process $q\bar{q} \to t\bar{t}g$ at one-loop
- One-loop amplitudes computed
  - Numerically with OpenLoops for leading-color contributions
  - Analytically for N_l pieces
- Subtraction terms constructed and implemented
  - Leading-color: [GA, Gehrmann-De Ridder, Meierhöfer, Pozzorini '14]
  - N_l: [GA, Gehrmann-De Ridder (in preparation)]
- Pointwise cancellation of explicit IR poles checked analytically in both cases

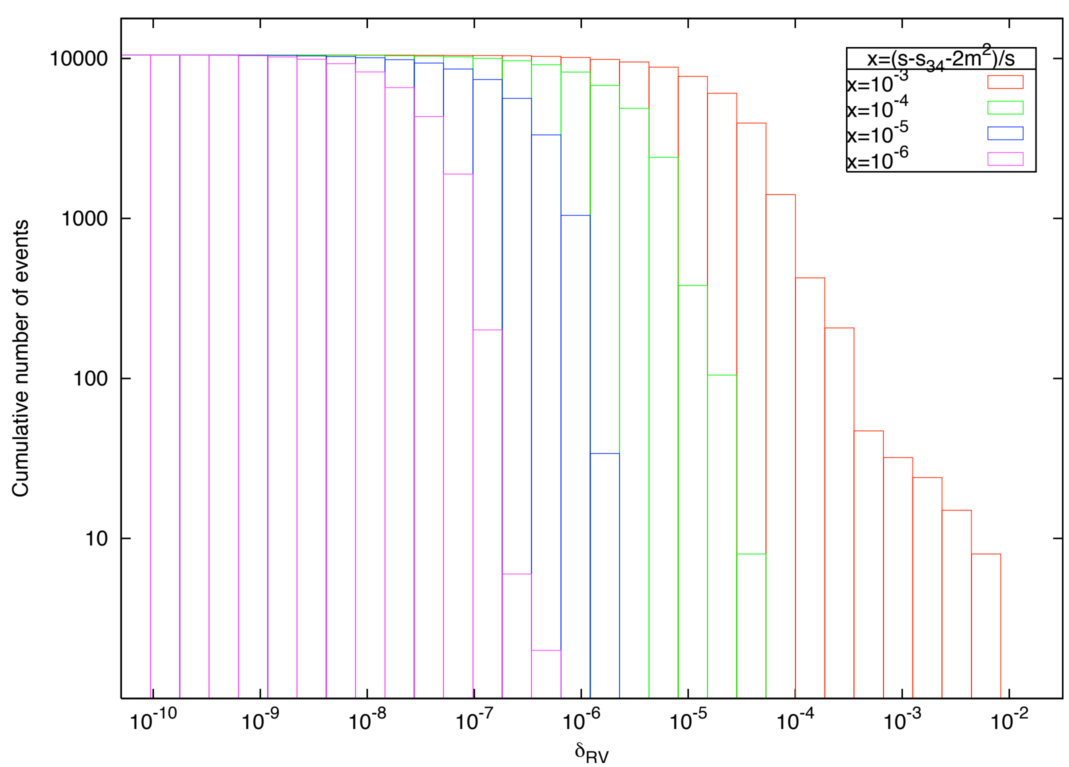
$$\boxed{\mathcal{P}oles\left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{VS}_{NNLO} + \mathrm{d}\hat{\sigma}^{MF,1}_{NNLO} + \int_1 \mathrm{d}\hat{\sigma}^{S,1}_{NNLO}\right) = 0}$$

Real Virtual Contributions

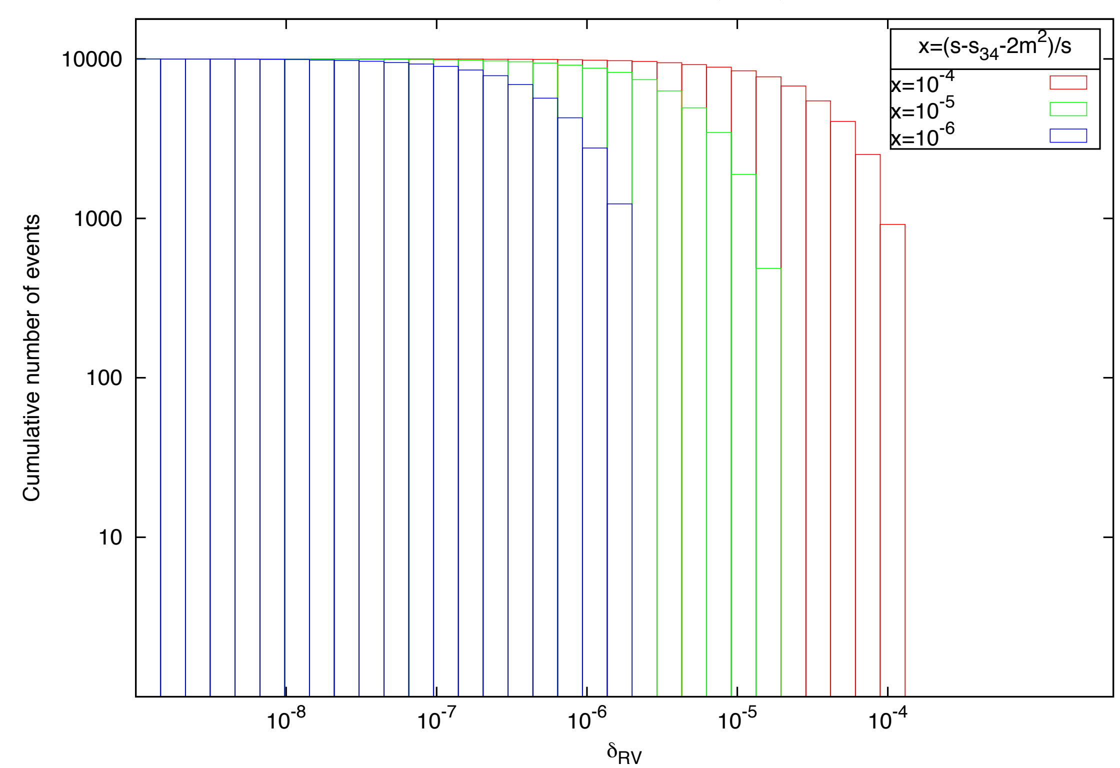
- Check of convergence. Analogous to double real check
  - Good convergence observed in N_l piece in soft and collinear limits
  - Good convergence observed in collinear limit of leading color piece
  - Convergence in soft limit of leading-color piece only achieved evaluating $\mathrm{d}\hat{\sigma}^{RV}_{NNLO}$ in quadruple precision

$$\delta_{RV} = \left| \frac{\mathcal{F}inite(\mathrm{d}\hat{\sigma}^{RV}_{NNLO})}{\mathcal{F}inite(\mathrm{d}\hat{\sigma}^{T}_{NNLO})} - 1 \right|$$

Soft limit (leading-color)



Soft limit (N_l)



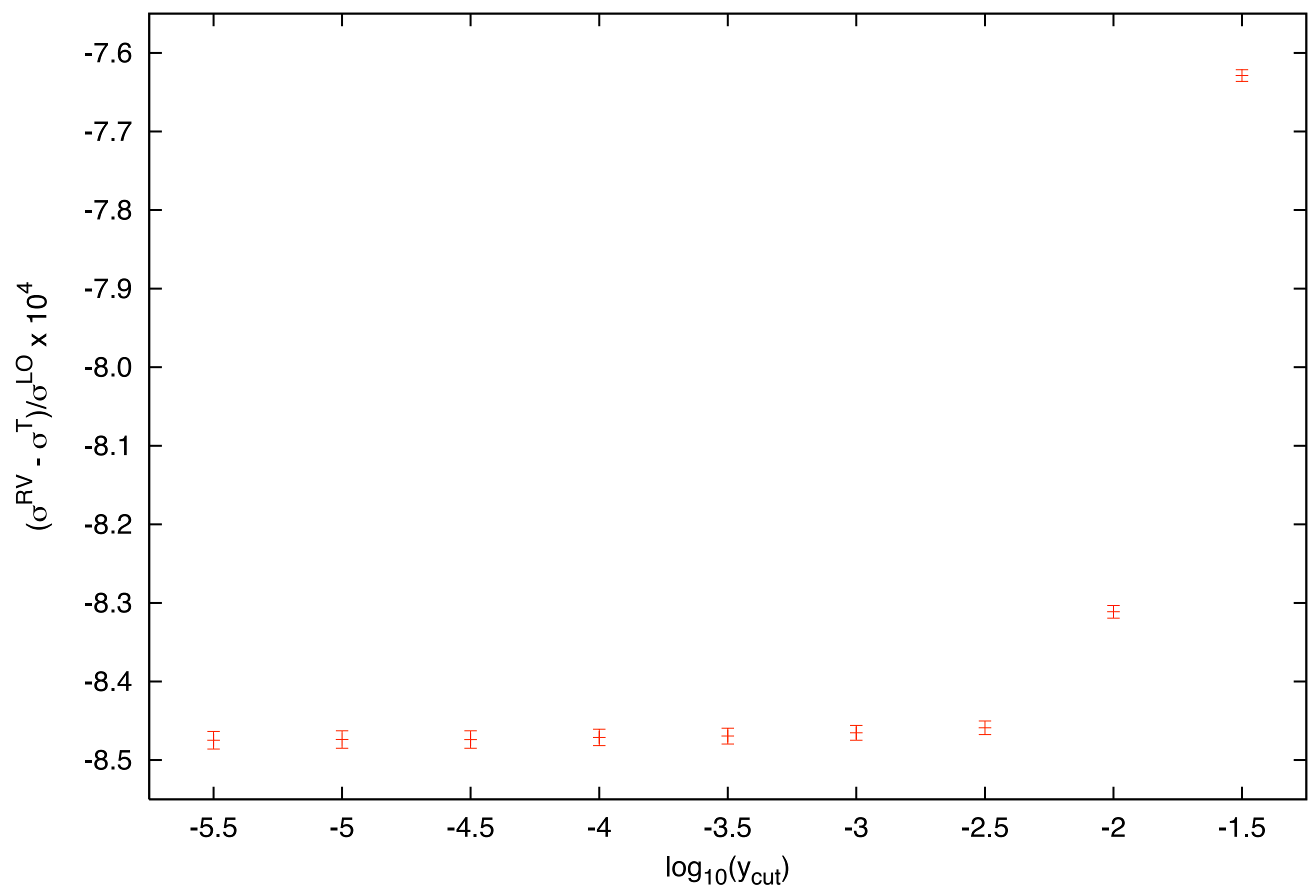
Real Virtual Contributions

Only "bad points" are (re)evaluated by OpenLoops in quadruple precision

- Fraction of quadruple precision evaluation in $\int_{\mathrm{d}\Phi_3}\left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{T}_{NNLO}\right)$?
- Is the integration stable?

Stability check: Evaluate $R = \left(\sigma^{RV}_{NNLO} - \sigma^{T}_{NNLO}\right)/\sigma_{LO}$ as a function of $y_{cut} = p_T^g/\sqrt{\hat{s}}$

- Integration is stable
- R has a plateau for $y_{cut} < y_{cut}^{max} \sim 10^{-3}$
- Strong check of our subtraction terms
- We can run with $y_{cut} \sim 10^{-4}$. Only ~0.01% points require quadruple precision.
- Efficient evaluation in double precision for the vast majority of points



Double Virtual Contributions

The ultimate check:

$$\boxed{\mathcal{P}oles\left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO} + \mathrm{d}\hat{\sigma}^{MF,2}_{NNLO} + \int_1 \mathrm{d}\hat{\sigma}^{VS}_{NNLO} + \int_2 \mathrm{d}\hat{\sigma}^{S,2}_{NNLO}\right) = 0}$$

- Pole cancellation verified analytically in Nl piece

```
Pole1LC =
 Simplify[
  Simplify[Coefficient[TwoLoopPolesLC, ep, -1] Delta[1 - x1] Delta[1 - x2] + Coefficient[OneTimesOneLoopPolesLC, ep, -1] Delta[1 - x1] Delta[1 - x2] -
     Coefficient[SubTermLC, ep, -1]] //. RepsLogsLC]

0
```

  - Non-trivial check on new integrated massive antennae
  - Proves applicability of NNLO antenna subtraction to reactions with massive fermions

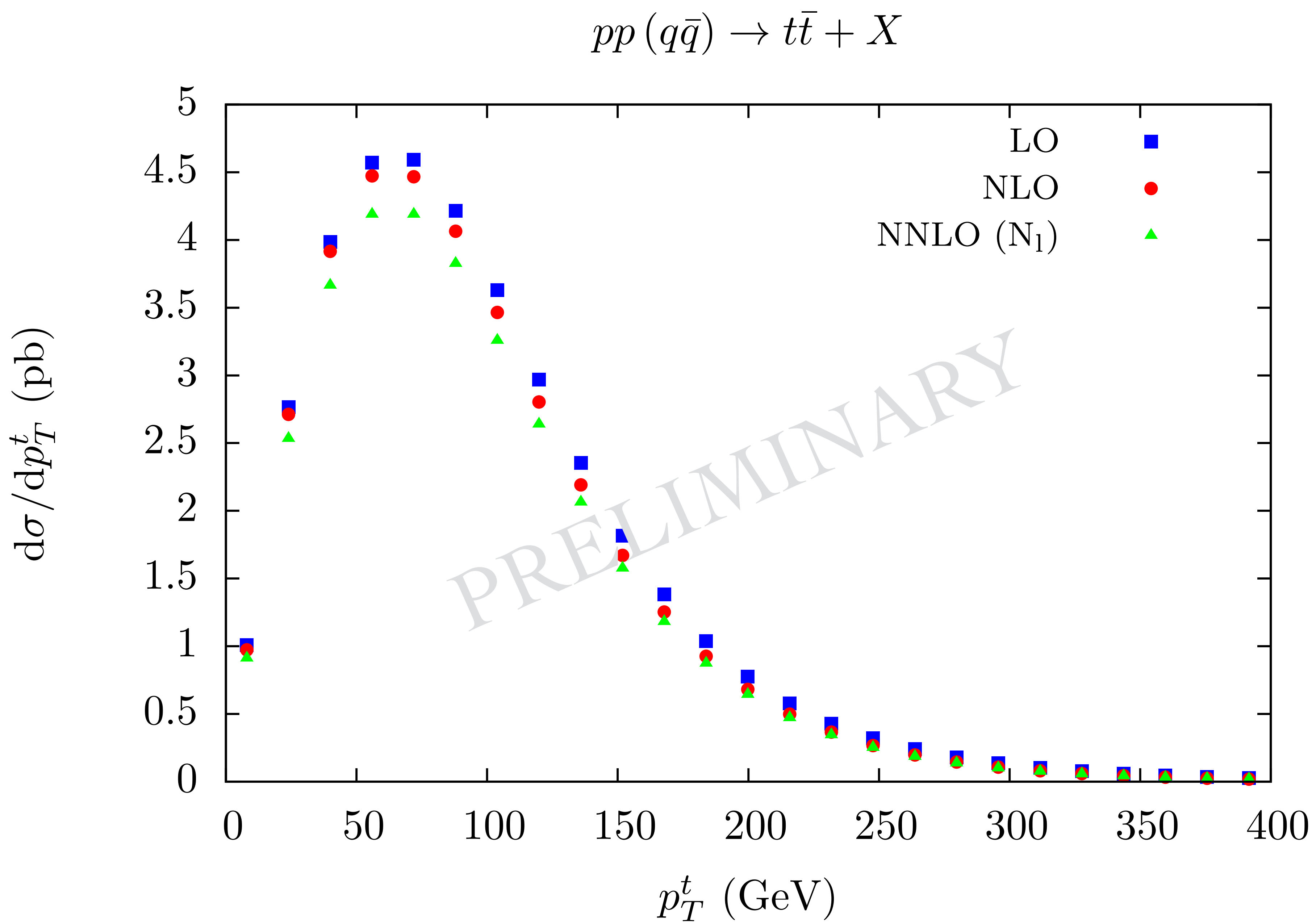
- Pole cancellation in leading color contributions in progress

Preliminary Results

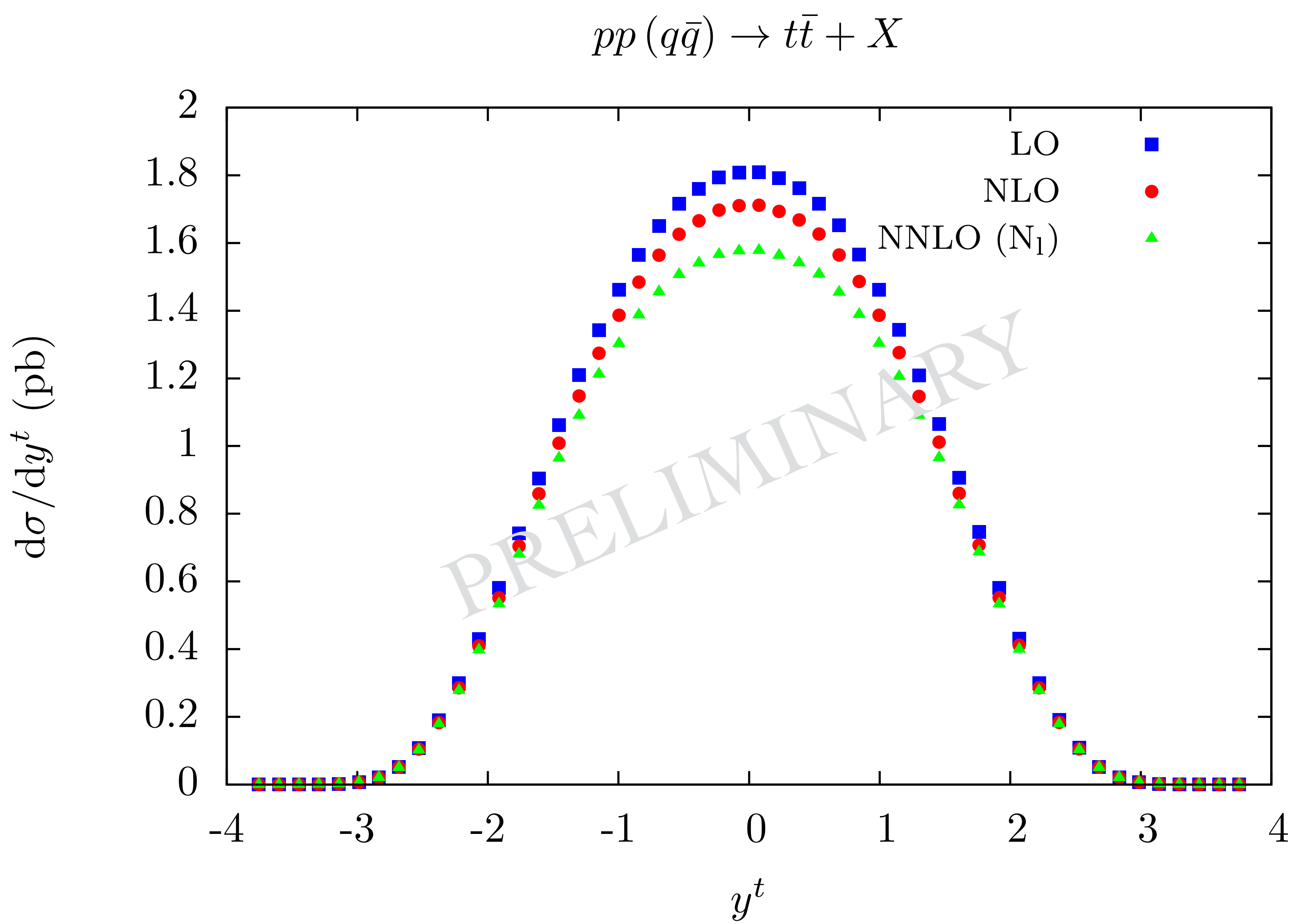
- Preliminary results for $pp(q\bar{q}) \to t\bar{t} + X$ (N_l only)
  - $\sqrt{s} = 8\,\mathrm{TeV}$
  - $m_{top} = 173.5\,\mathrm{GeV}$
  - $\mu = m_{top}$
  - MSTW2008NNLO PDF sets

> Warning: The following NNLO results contain the N_l contributions to the $q\bar{q}$ channel only. They are presented as a proof of principle. Strong phenomenological conclusions are not recommended.

Preliminary Results

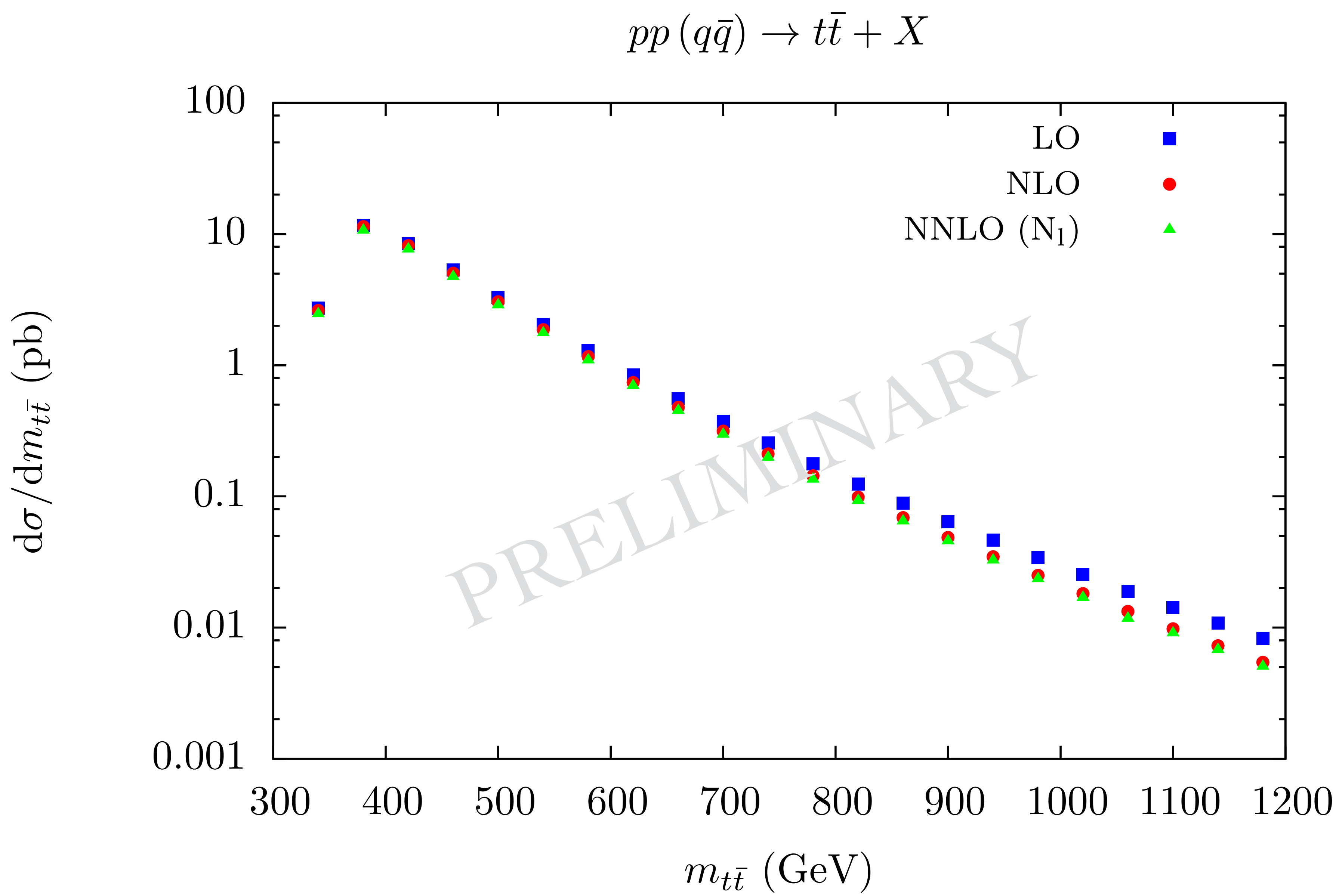


Preliminary Results



Could NNLO effects have an impact on our theory prediction for A_{FB} at Tevatron?

Preliminary Results



Summary And Outlook

- Fully differential NNLO calculation for $t\bar{t}$ production in the $q\bar{q}$ channel within reach (leading-color + fermionic contributions)
- Double real contributions: subtraction terms implemented and tested
- Real-virtual contributions:
  - Subtraction terms implemented and tested
  - Precise and stable one-loop amplitudes from OpenLoops in leading-color part
- Double virtual contributions:
  - Two-loop amplitudes available (for leading color and fermionic pieces)
  - Analytic pole cancelation in N_l part
- Event generator implemented and working (with N_l part for the moment)

<u>Outlook</u>

- Complete leading-color double virtual contributions in $q\bar{q}$ channel
- Phenomenology in $q\bar{q}$ channel. A_{FB}, main goal
- Include gg and qg channels